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# Finite Element Modeling of the Upsetting of an Anisotropic Cylindrical Workpiece

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**Abstract.** Anisotropic material deformation is modeled with the application of the finite element method. Hill's yield criterion is used for simplified conditions of the upsetting process. The largest flow stress direction is determined to be parallel to all the three coordinate axes by turns. It is discovered that the base of the cylinder can take an oval shape when the flow stress directions of various values lie in the base plane. In this case, the smaller axis of the oval corresponds to the largest flow stress direction. When the flow stress directions of various values lie in the longitudinal section plane of the workpiece, its shape remains cylindrical. The deformation load is higher in this case.

## INTRODUCTION

Modeling of deformation processes with the application of the finite element method has found wide application in metal forming, where the solution of the boundary value problem in most cases involves the application of the hypothesis of deformable medium isotropy. The use of this hypothesis may lead to inaccuracy in calculations, since it does not take into account the quality of the properties of materials being deformed. Many deformable materials have a certain level of anisotropy, which results from the asymmetric lattice structure (magnesium [1], titanium [2]) or from preferred grain orientation acquired as a result of directed heat transfer [3] and/or deformation [4]. It is possible to consider deformed medium anisotropy using the corresponding yield criterion. The analysis of the studies reporting boundary value problem solution results for such metal forming processes as rolling, extrusion, drawing and die-forging has shown that the von Mises yield criterion is used in modeling. The use of the yield criterion for an anisotropic medium can ensure a higher accuracy of the calculation results [5]. In this case, before the modeling of complex metal forming processes, it is necessary to verify the solution validity using a new yield criterion for the simplified conditions of the test problem.

The aim of this study is to estimate the consequences of substituting the anisotropy hypothesis for the isotropy hypothesis in solving the problem of cylindrical workpiece upsetting.

## FEM ANALYSIS AND EXPERIMENTAL PROCEDURE

In this paper, the deformation of anisotropic plastic medium with isotropic hardening is modeled. The yield criterion in this case is set by Hill's model [6] as

$$F(\sigma_{YY}-\sigma_{ZZ})^2+G(\sigma_{ZZ}-\sigma_{XX})^2+H(\sigma_{XX}-\sigma_{YY})^2+2L\sigma_{YZ}^2+2M\sigma_{ZX}^2+2N\sigma_{XY}^2=1\,, \tag{1}$$

where $F$, $G$, $H$, $L$, $M$ and $N$ are the anisotropy coefficients, $\sigma_{ij}(i,j=X,Y,Z)$ are the stress deviator components.

It is shown in [6] that, if the yield criterion represented by Eq. (1) is applied to particular cases of three uniaxial tensions in the directions of *X, Y* and *Z*, the anisotropy parameters can be described by the following formulae:

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$$F = \frac{1}{2}\left[\frac{1}{\sigma_{YY}'^2} + \frac{1}{\sigma_{ZZ}'^2} - \frac{1}{\sigma_{XX}'^2}\right]; G = \frac{1}{2}\left[\frac{1}{\sigma_{ZZ}'^2} + \frac{1}{\sigma_{XX}'^2} - \frac{1}{\sigma_{YY}'^2}\right]; H = \frac{1}{2}\left[\frac{1}{\sigma_{XX}'^2} + \frac{1}{\sigma_{YY}'^2} - \frac{1}{\sigma_{ZZ}'^2}\right]; \quad (2)$$

$$L = \frac{1}{2\sigma_{YZ}'^2}; M = \frac{1}{2\sigma_{ZX}'^2}; N = \frac{1}{2\sigma_{XY}'^2}, \quad (3)$$

where $\sigma_{ij}'(i, j = X, Y, Z)$ is the yield strength in different directions.

It follows from formulae (2) and (3) that, to find the material anisotropy coefficients, it is necessary to conduct quite a lot of experiments testing the material in several directions. In the context of the test problem, the anisotropy coefficients can be determined analytically. Let us assume that the material to be deformed has sufficient anisotropy and that the yield strength in the $X$ direction is twice the amount of its analogue for the $Y$ and $Z$ directions,

$$\sigma_{XX}' = 2\sigma_{YY}', \sigma_{YY}' = \sigma_{ZZ}', \quad (4)$$

then, from formulae (2), it is possible to obtain the following ratios:

$$F = 0.875\frac{1}{\sigma_{YY}'^2}; G = H = 0.125\frac{1}{\sigma_{YY}'^2}, \quad (5)$$

$$\frac{F}{G} = \frac{F}{H} = 7. \quad (6)$$

Similarly, the ratios of the anisotropy coefficients for the situations of anisotropy in the $Y$ and $Z$ directions, respectively, are obtained,

$$\frac{G}{F} = \frac{G}{H} = 7, \quad (7)$$

$$\frac{H}{F} = \frac{H}{G} = 7. \quad (8)$$

The ratio of the parameters for three variants of their prescription is presented in Table 1.

**TABLE 1.** Anisotropy coefficients for different variants of modeling

| **Variant** | **Flow stress ratio** | **Ratio of anisotropy coefficients** |
|---|---|---|
| 1 | $\sigma_{XX}' = 2\sigma_{YY}' = 2\sigma_{ZZ}'$, $\sigma_{YY}' = \sigma_{ZZ}'$ | $\frac{F}{G} = \frac{F}{H} = 7$ |
| 2 | $\sigma_{YY}' = 2\sigma_{ZZ}' = 2\sigma_{XX}'$, $\sigma_{ZZ}' = \sigma_{XX}'$ | $\frac{G}{F} = \frac{G}{H} = 7$ |
| 3 | $\sigma_{ZZ}' = 2\sigma_{XX}' = 2\sigma_{YY}'$, $\sigma_{XX}' = \sigma_{YY}'$ | $\frac{H}{F} = \frac{H}{G} = 7$ |

The problem is solved in the simplest possible way in order to estimate directly the influence of the anisotropy of the medium on forming. The hardening law for a deformable medium is determined from the reference book [7] as

$$\sigma_f = 400 + 112\varepsilon^{0.38}, \quad (9)$$

where $\sigma_f$ is the flow stress of the steel, $\varepsilon$ is the amount of strain.

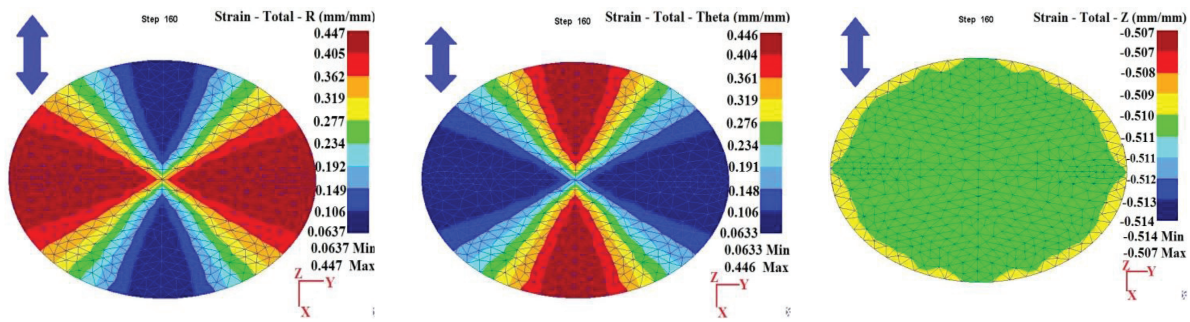
The ration of the coefficients $L$, $M$ and $N$ are taken for all the variants on the basis of the data acquired from [8],

$$\frac{L}{M} = \frac{M}{N} = 1 . \tag{10}$$

The workpiece is set to be cylindrical with the diameter $D_0 = 100$ mm and the height $h_0 = 100$ mm. The formation temperature is set to be 20 °C. A finite element mesh with 16,000 elements, with the minimum element size of 2.36 mm is constructed on the workpiece. The deforming instrument comprises 2 completely rigid smooth plates with the diameter $D_p = 200$ mm. The percent reduction value is $\varepsilon = 40\%$. The friction condition on the contact surface is set by the Coulomb law, with $\mu = 0.0001$, which imitates upsetting without friction. The problem is solved in the DEFORM-3D software, with the position of the axis of the cylindrical workpiece along the $Z$ axis, the two orthogonal axes being labeled, respectively, as $X$ and $Y$.

## RESULTS

The distribution of the stress components $\sigma_{ij}$ and the amount of strain $\varepsilon_{ij}$ are obtained from the modeling results; for the analysis of the results, a cylindrical coordinate system $r$, $\varphi$, $z$ is assumed. In accordance with variant 1 (Table 1), the highest strength characteristic corresponds to the direction of the $X$ axis. Strain distribution in the direction of the axial coordinate in case of anisotropy in the workpiece base plane must prove to be uniform; therefore, Fig. 1 presents the image of the cross section form and the planar strain distribution.

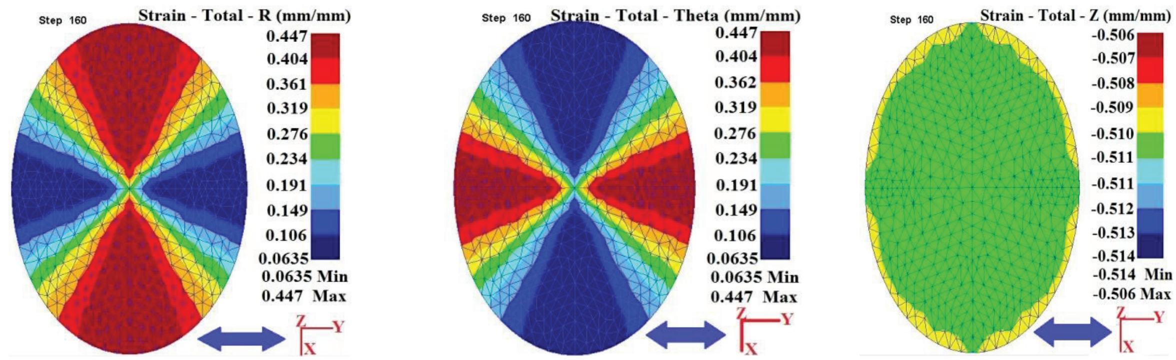



(a) (b) (c)

**FIGURE 1.** The images of the workpiece cross section and strain distribution (colored areas) for $\sigma'_{XX} = 2\sigma'_{YY}, \sigma'_{YY} = \sigma'_{ZZ}$; $F = 7G$, $G = H$, the direction of the highest strength properties of the material are shown by a double arrow.

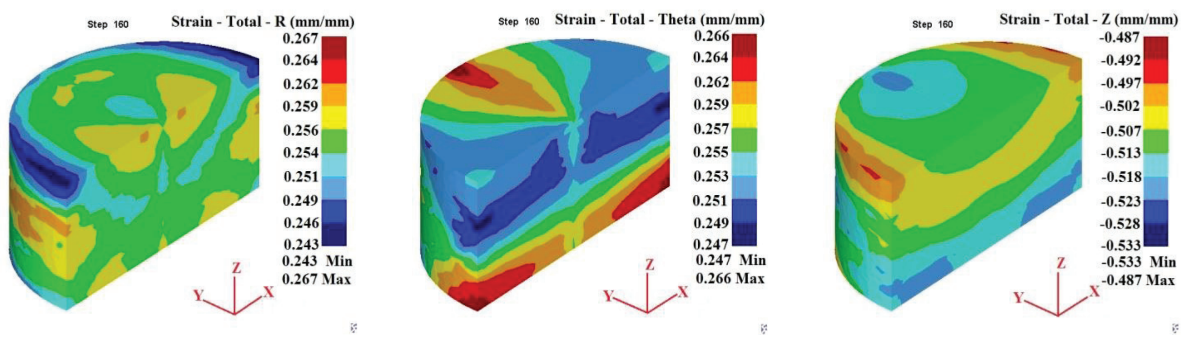
The solution shows that the initial round shape of the base changes into an oval one, the smaller axis of the oval points in the direction of the vector of the highest strength properties, the axes ratio being close to 1.5. The deformation takes place in the direction of the lowest flow stress. The calculated amount of strain $\varepsilon_{rr}$ (Fig. 1a) is close to zero in the direction of the shorter oval axis, and it is the highest along the longer axis. The maximum value is about 0.45. For the tensor component $\varepsilon_{\varphi\varphi}$ (Fig. 1b), the maximum and the minimum change places. The third tensor component $\varepsilon_{zz}$ can be found from the volume constancy condition; at the same time, Fig. 1c shows that the algebraic addition of the nonuniform distribution patterns $\varepsilon_{rr}$ and $\varepsilon_{\varphi\varphi}$ gives a uniform distribution pattern of the $\varepsilon_{zz}$ component.

In the calculations for variant 2 (Table 1), the highest strength property corresponds to the direction of the $Y$ axis. The forming of the workpiece cross section proves to be reverse to that in the first variant (Fig. 2a, b); however, the principle that the smaller oval axis points in the direction of the highest flow stress value is preserved. The independence of strain distribution in the cross section from the $X$ and $Y$ coordinates is confirmed (Fig. 2c).




(a) (b) (c)

**FIGURE 2.** The images of the workpiece cross section and strain distribution (colored areas) for $\sigma'_{YY} = 2\sigma'_{ZZ}, \sigma'_{ZZ} = \sigma'_{XX}$; $G = 7F$, $F = H$, the direction of the highest strength properties of the material are shown by a double arrow.

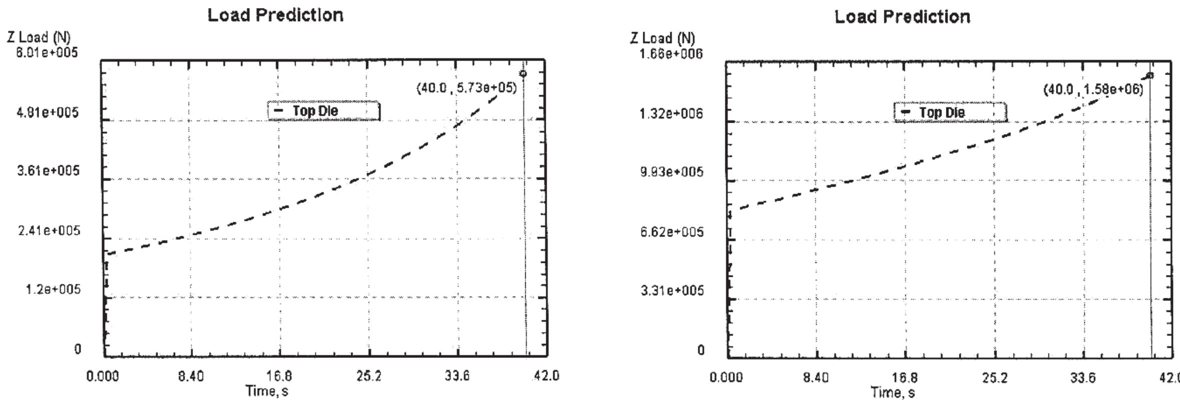



(a) (b) (c)

**FIGURE 3.** Strain distribution (colored areas) for $\sigma'_{ZZ} = 2\sigma'_{XX}, \sigma'_{XX} = \sigma'_{YY}$; $H = 7F$, $F = G$.

Variant 3 (Table 1) is calculated for the following flow stress ratio: $\sigma'_{ZZ} = 2\sigma'_{XX}, \sigma'_{XX} = \sigma'_{YY}$, i.e. the highest strength property corresponds to the direction of the *Z* axis. A special feature of this variant is that the strength properties along the *X* and *Y* directions are the same, and so must be the workpiece forming in the horizontal projection. Indeed, in this case, the cylinder base remains round after deformation; therefore, Fig. 3 shows only epy longitudinal section of the workpiece. It is clear that the amount of strain along the *X* and *Y* axes changes in a narrow range from 0.24 to 0.27 (Fig. 3a, b), and that along the *Z* axis varies from 0.49 to 0.53 (Fig. 3c).

A difference in energy-power parameters of deformation has been found. The deformation load is 573 kN for variants 1 and 2 (Fig. 4a) and 1580 kN, i.e. significantly higher, for variant 3 (Fig. 4b). This phenomenon is explained by the change of the metal stress state depending on the directions of the maximum strength properties of the workpiece. In case the highest strength property of the material is in the plane of the specimen base (variants 1 and 2), the principal stress value in the direction of deformation is -179 MPa. For variant 3, where the highest strength property corresponds to the *Z* direction, the principal stress value in the direction of deformation is significantly higher and equals -494 MPa.




(a) (b)

**FIGURE 4.** The diagram of deformation load variation for different anisotropy coefficients.

## CONCLUSION

The FEM solution of the test problem of anisotropic medium upsetting has shown that the use of Hill's yield criterion enables one to describe metal forming and the stress-strain state in the deformation zone with a high level of validity.

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